National Exams

Met-A2, Metallurgical Rate Phenomena

3 hours duration

NOTES:

1. If doubt exists as to the interpretation of any question, the candidate is urged to submit with the answer paper, a clear statement of any assumptions made.
2. This is an CLOSED BOOK EXAM.
   An approved Casio or Sharp calculator is permitted.
3. FIVE (5) questions constitute a complete exam paper.
   The first five questions as they appear in the answer book will be marked.
4. Each question is of equal value.
5. One aid sheet 8x1/2 x 11 written on both sides is permitted.

Met-A2 Metallurgical Rate Phenomena

Answer question number one, plus any four others. Open Book

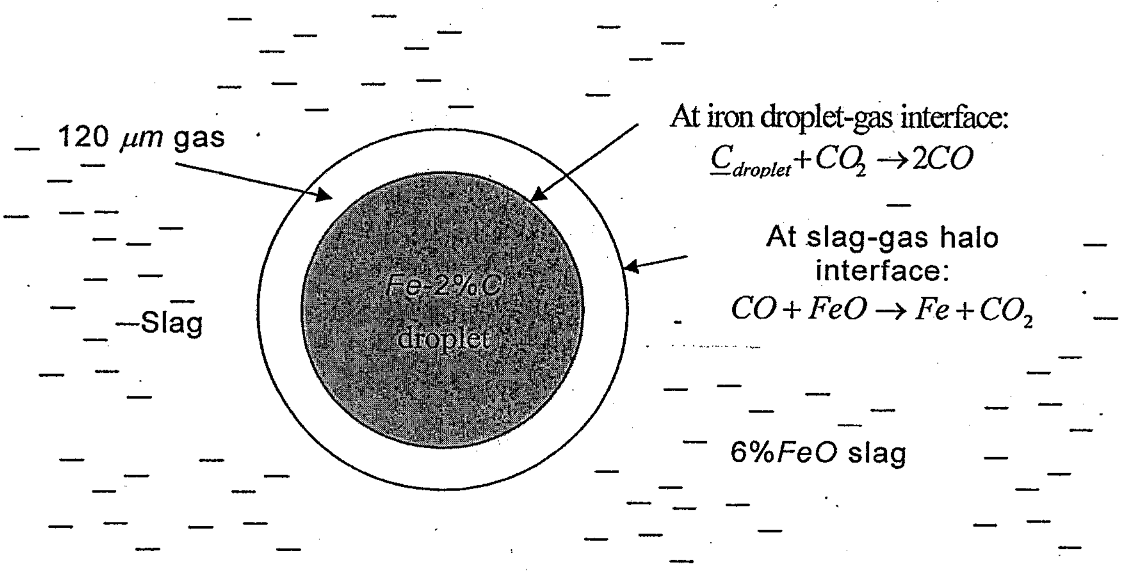
1. General knowledge questions to be answered by all candidates. Answer true, false, or ambiguous, and briefly explain your reasoning.

   a. Ficks 1st Law of diffusion for one dimensional mass flow can be written $\dot{N}_Z'' = -D_{A/B}\dfrac{\partial C_A}{\partial x}$
   b. Fick's law can also be written in another form to take into account molar convection of species for gaseous diffusion?
   c. Write down Newton's equation of viscosity. This equation applies to gases and also to slags and liquid metals?
   d. The viscosity of a gas increases with pressure and temperature?
   e. The thermal conductivity of a metal normally drops significantly on transforming from the solid to the liquid state.
   f. If the contact angle, ϕ, of a liquid wetting the surface of a container is 0°, sketch the shape of a bubble entering such a liquid through a small orifice set in the bottom of such a container.
   g. The kinetic theory of gases predicts that the thermal conductivity of a gas increases with the square root of absolute temperature, as does its viscosity.
   h. The kinetic theory of gases predicts that the viscosity of gas increases with absolute pressure
   i. The solubility of oxygen in solid iron is zero.
   j. A well mixed reactor is less efficient than a plug flow reactor for most, but not all, orders of reactions?
   k. The Froude number represents the ratio of gravitational to inertial forces, while the Reynolds number represents the ratio of inertial to viscous to forces.
   l. Fourier's Second Law of heat conduction contains the thermal conductivity of a substance in the thermal diffusivity term?
   m. The difference between the Biot number and the Nusselt number relates to the thermal conductivity of the phases?
   n. Liquid metals have relatively thick thermal boundary layers as compared to gases and ionic liquids?
   o. Radiation can be transmitted, reflected, and/or absorbed?

2. In the direct steelmaking reactor based on the reduction of an oxidizing foaming slag by char (carbon) particles and droplets of iron containing 2% carbon, it is postulated that the rate controlling step governing the reduction of *FeO* within the slag is the transfer of *CO* and CO_2 across gas halos surrounding the iron droplets and char particles. In *AISI* plant trials, the smelting rate of iron was observed to be 4 *tonnes/hr* of *Fe,* for a slag *FeO* content of 6 *wt%*, and a slag weight of 40 *tonnes.* Estimate the total surface area of char and iron droplets needed to achieve the smelting rates observed. Assuming the average char and droplet diameters to be 1 *cm,* estimate the volumetric loading (i.e. volume percentage) of droplets and char corresponding to these smelting conditions. State any assumptions you see fit.

Data:

Atomic weight of *Fe*	: 56 g/mol
Gas constant, *R*	: 8.314 *J/mol·K*
Temperature of Foaming Slag	: 1600 °*C*
Volume %CO_2 in gas phase halos at slag interfaces	: 6 %
Gas pressure within halos	: 1.2 *atm*
Gaseous Diffusion Coefficients ($D_{CO} = D_{CO_2}$)	: 1.0×10^{-3} m^2/s
Density of molten slag	: 3300 kg/m^3



3. A hot rolling mill superintendent considered the possibility of increasing his mill's tonnage capacity by increasing the lengths of the slabs charged to the reheat furnaces. These slabs are rolled down to 32-mm-thick "transfer bars" in the rougher stand, from which they exit at 1590 *K*, and then pass along an entry (or holding) table into the finishing stands. Slab temperature rundown during this period is an important constraint on the finishing operation; in order to avoid overloading the electric motors running the finishing stands, the slab temperature must never drop below 1422 *K* on entry into stand F1. Assuming the critical conditions of a minimum lag of 5 *s* between each slab and a coiling speed of 20 *m/s* on 2.3 *mm* gauge material, calculate the maximum thickness of slab that could be handled by the operation, and the new theoretical annual mill capacity (i.e. tonnes/annum on a 24 hour basis of operation with no shut-downs producing 2.3 *mm* gauge material). For the purposes of this calculation, ignore temperature gradients across the slab, natural convection from the slab surfaces, conduction into rollers and, finally, back-radiation from the plant.

Data:

Density of steel slab (transfer bar) : 7450 kg/m^3
Thickness of transfer bar : 32 *mm*
Temperature of slab on exit from rougher : 1590 *K*
Minimum temperature of slab entering finishing stands : 1422 *K*
Slab thickness : 0.61 *m*
Width of slab : 1.21 *m*
Heat capacity of slab : 0.45 $kJ/kg{\cdot}K$
Thickness of strip : 2.3 *mm*
Coiling speed (speed of strip) : 20 *m/s*
View factor of slab, $F_{slab/\infty}$: 1
Emissivity of slab : 0.8
Stefan-Boltzmann constant : $5.67\times10^{-8}\ W/m^2{\cdot}K^4$

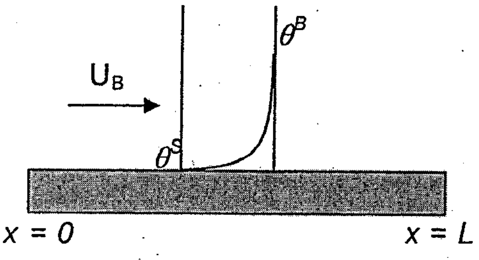
4. Liquid Metal Flows at a velocity U and temperature θ^B over a flat plate of length L, held at temperature θ^S, in plug flow. Solve for the developing temperature profile within the liquid metal (assume semi-infinite approximation with a fixed value at the interface), as it flows across the surface and thereby show that the interfacial heat flux;

$$\dot{q}'' = -\frac{k\left(\theta^B - \theta^s\right)}{\sqrt{\pi\alpha t}}$$

Show that this can be expressed in the form

$$Nu_x = \sqrt{\frac{\mathrm{Re}_x \cdot \mathrm{Pr}}{\pi}}$$

where; $h \equiv \dfrac{\bar{\dot{q}}''}{\theta^B - \theta^S}$.

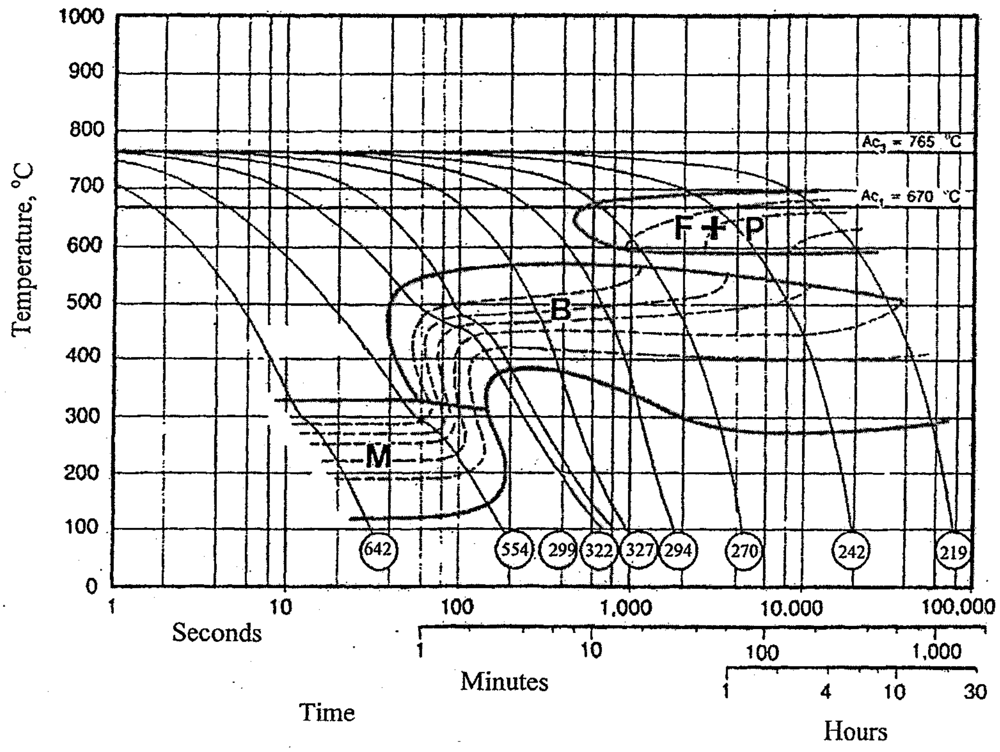


5. In the production of a Samurai Sword, it is necessary for the cutting edge of the sword to transform to a martensite microstructure, but for the main body of the sword to form an upper bainite microstructure for toughness. To accomplish this, the thicker part of the sword must pass through the "nose" of the CCT diagram, so that the austenite transforms to the upper bainite. Given the attached TTT diagram for an hypo-eutectoid carbon steel, estimate the maximum critical heat flux that can be tolerated without transforming the body of the sword to martensite.

Data

Sword thickness = 5 mm, Carbon content of steel = 0.45%, M_s temperature = 325°C
Thermal conductivity of steel = 80 W/m K
Heat capacity of steel = 0.450 kJ/kg K
Density of steel = 7,860 kg/m^3
Critical heat fluxes to water during quenching of clay-coated sword = ?? MW/m^2
Initial temperature of sword prior to quenching = 800 °C

Hint; you may assume a low Biot number (hL/k less than 0.1) and therefore neglect temperature gradients within the cross-section of the sword itself.



Considering the TTT diagram for a hypo-eutectoid steel, presented in the Figure above, calculate the cooling rates needed, in order to obtain 1) a F+P (ferrite and pearlite) microstructure with a hardness of 242HB, and 2) a fully martensitic (M) microstructure of hardness 554HB.

6. Some 28% of cold scrap is used in order to prevent turn-down steel temperatures exceeding 1600 degree C in typical North American top blown BOF operations. What is the amount of heat absorbed in heating this scrap, in MJ/tonne, to 1600°C, given the following data?

$\rho_{steel,solid} = 7500 kg/m^3$

$C_p(solid) = 0.45 kJ/kg.K$

$C_p(liquid) = 0.717 kJ/kg.K$

$\rho_{steel,liquid} = 7000 kg/m^3$

$LatentHeat_{steel} = 271 kJ/kg$

Melting point of steel = $1520^0 C$

Room Temp = $20^0 C$

Estimate the temperature the steel would have risen to, if the 30% scrap had not been added to the hot metal. You can ignore the heat required for the slag, as it is small.

7. Aluminum wire is fed into a 3 metre deep bath of liquid steel contained in a steelmaking teeming ladle. The temperature of the 0.07wt% Carbon steel bath is at 1600°C at the strong stir ladle station. We want the 1cm diameter aluminum wire to melt and be dispersed within the liquid steel bath at a depth of 2.7 metres. Develop a general expression which will allow you to estimate the wire velocity required (metres per second) to do this. You may use the following data, as necessary;

DATA

Latent heat of steel = 271 kJ/kg
Latent heat of aluminum 387 kJ/kg
Melting point of 0.07%C steel = 1500 °C
Melting point of aluminum = 660 °C
Density of aluminum = 2700 kg/m^3
Density of liquid steel = 7000 kg/m^3
Heat Capacity of solid aluminum = 0.902 kJ/kg K
Heat capacity of liquid aluminum = 1.09 kJ/kg K
Heat capacity of liquid steel = 0.75 kJ/kg K
Thermal conductivity of liquid steel = 28 W/m K
Viscosity of liquid steel at melting point = 7 mPa s

For heat transfer to the surface of the wire, you may use the correlation $Nu_L = 1.12\ Re^{0.5}\ Pr^{0.5}$ to deduce heat inputs. Experimentally, Mucciardi and Guthrie have shown that;

Depth of release (m) = Wire Dia.(m) $^{0.86}$ * Wire Velocity $^{0.52}$ / Superheat (K)$^{0.34}$
Compare your two answers, and explain the difference.

8. Briefly discuss the use of flow controls and impact pads in tundishes that are used to reduce the numbers of inclusions reporting to the strands of continuous casting moulds.

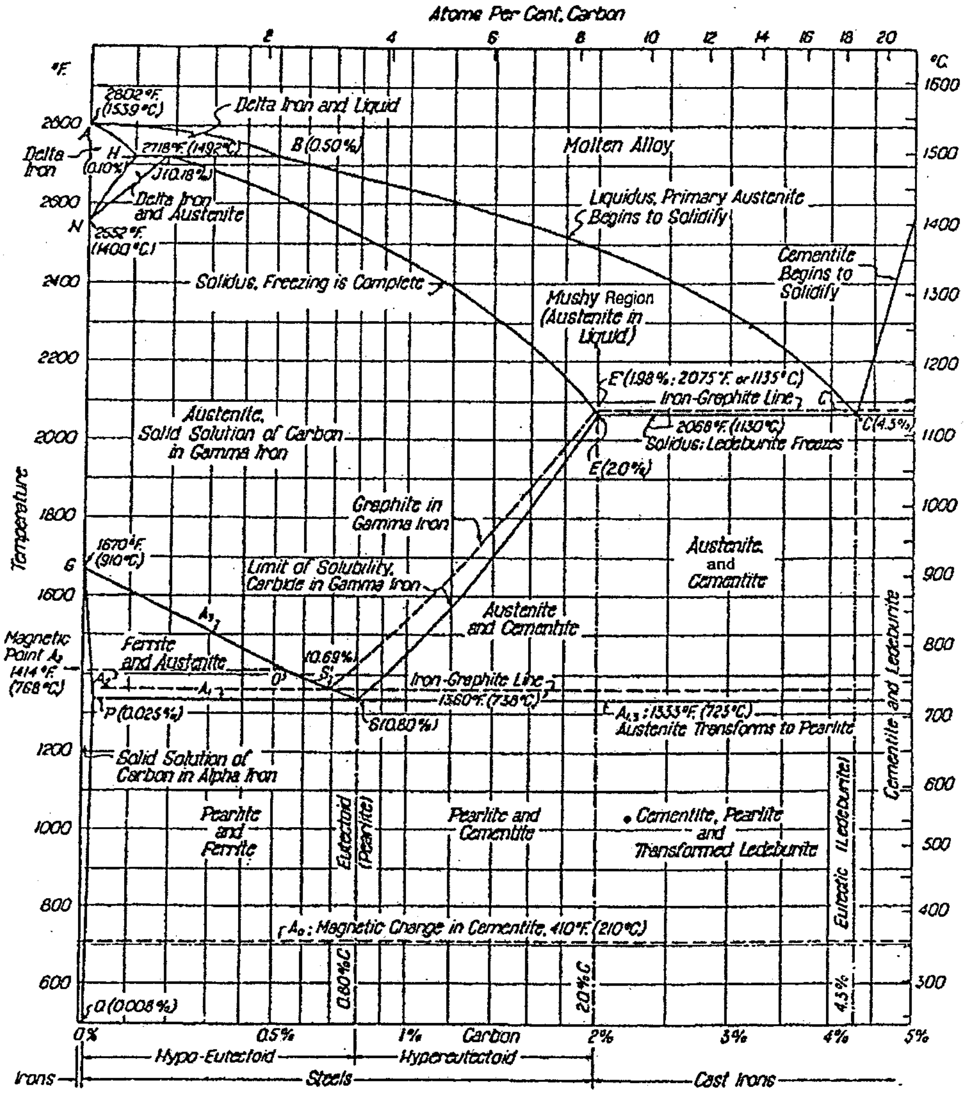
Assuming we have a tundish containing liquid steel, from which we wish to remove all inclusions below 50 microns in diameter. The question is HOW? Calculate the Stokesian rise time for a typical 25 micron spherical inclusion of alumina to float to the surface of the steel, from a depth of 500 mm. If we were able to produce micro-bubbles of argon, we could use those bubbles to transport such small inclusions to the surface in a shorter time, through their attachment to the bubble surfaces. Assuming, therefore, that we can produce 0.06mm diameter (600 micron) argon bubbles within the tundish, what will their float out time be, by comparison, under the same conditions? Given a typical tundish residence time of eight minutes, what are the chances of floating out either?

Data; $F_{drag} = 6\pi\mu r U_{\infty}$, μ_{steel}= 7mPa s, $\rho_{Al2O3} = 3000$ kg/m^3, $\rho_{argon} = 1$ kg/m^3

9. Determine the initial exit velocity (m/s) at which liquid steel will drain from a cylindrical steelmaking ladle, filled to a height, H_o, of 3 metres, and fitted with a ladle shroud of length, L =1.5 m. The connection between the two is perfectly tight, so there is no leakage of air into the shroud at the joint. This situation corresponds to a new ladle being opened and steel pouring into a tundish, during continuous casting operations. Also, initially, the liquid steel exits into the air above the liquid steel in the tundish. Similarly, the inner wall diameter of the ladle is 4m while the Internal Diameter of the ladle shroud, D, is 80 mm.

Develop a general expression, showing how the steel's velocity exiting the ladle shroud, depends on the height of steel in the ladle,H_o, the length of the ladle shroud, L,gravity, g, and the frictional energy losses as steel flows through the shroud ($E_f = 2f(L/D)V^2$, where V is the velocity of steel passing through the pipe. This last term appears in the Steady Flow Energy Equation, or Modified Bernoulli Equation, that is needed to solve the problem. Finally, you should assume a sharp entrance into the ladle shroud from the ladle, and an abrupt exit of steel from the nozzle, as it passes into air. Finally, calculate the numerical steel exit velocity for the data given.

This iron-carbon diagram can be useful for answering question 6



Ferrite = solid solution of carbon in lower temperature, body centered cubic form of iron.
Austenite = solid solution of carbon in the high temperature, face centered cubic form of iron.
Ledeburite = eutectic mixture of carbide and austenite
Cementite = iron carbide, Fe_3C.

The iron–carbon phase diagram. *Ferrite* = solid solution of carbon in the lower-temperature, body-centred cubic form of iron. *Austenite* = solid solution of carbon in the high-temperature, face-centred cubic form of iron. *Ledeburite* = eutectic mixture of carbide and austenite. *Cementite* = iron carbide, Fe_3C. *Pearlite* = mixture of ferrite and iron carbide. *Delta iron* = solid solution of carbon in the very-high-temperature body-centred cubic form of iron.